Final Report

Contract No: FA520904P0253

THZ Radiation Device Using High-T_c Superconducting Intrinsic Josephson Junctions

1) Basic Research Idea:

In highly anisotropic high-T_c superconductors, such as $Bi_2Sr_2CaCu_2O_{8+X}$ (Bi-2212) or $Tl_2Ba_2Ca_2Cu_3O_{10+X}$ (Tl-2223), the superconductivity takes place on 0.3-nm-thick CuO_2 planes. In a naturally grown $Bi_2Sr_2CaCu_2O_{8+X}$ single crystal approximately 1.2-nm-thick insulating layers are formed between adjacent CuO_2 superconducting layers. The insulating layers are thin enough so that they allow paired superconducting electrons tunnel through them at temperatures below the superconducting transition of CuO_2 layers, thus forming serially stacked Josephson pair-tunneling junctions. These built-in junctions stacked uniformly at a repetition interval of 1.5 nm are called intrinsic Josephson junctions (IJJs) (refer to Fig. 1).

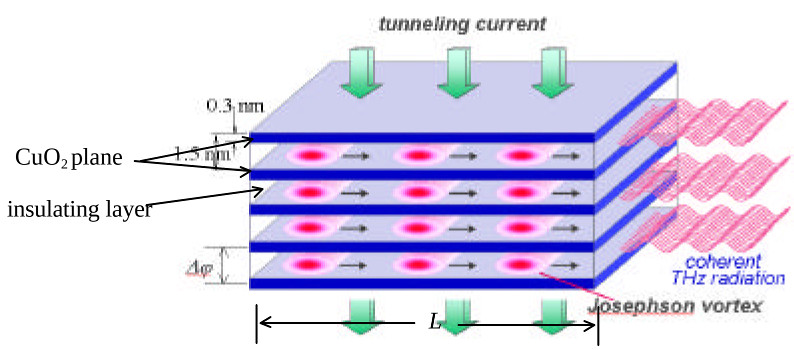

Fig. 1. Conceptual scheme of THz radiation from a stack of Bi-2212 IJJs.

whose length L is longer than the Josephson penetration depth l_J (long-junction limit), Josephson vortices are generated in insulating layers of IJJs. In a high vortex density corresponding to a field in the range of a few tesla and under a suitable current bias condition Jospehson vortices form a rectangular lattice as schematically illustrated in Fig. 1. By applying a Josephson tunneling bias current (of density 10^3 ampere/cm^2), the rectangular Josephson vortex lattice is driven by the Lorentz force along the junctions (refer to Fig. 1) at an extremely high speed close to 0.1-1% of the speed of light. The fast change of the superconducting phase difference, $d\Delta\varphi/dt$, resulting from the fast vortex motion across superconducting CuO_2 electrodes, leads to an excitation of THz-range plasma oscillation in the junction, which in turn can be converted to a THz-range electromagnetic radiation at the boundary of a stack of IJJs. Since the radiation is caused by the in-phase motion of a rectangular vortex lattice formed over multiple junctions it is coherent with its power increasing in proportion with the square of the number of stacked junctions. It is expected to be not difficult to get power in the range of a fraction of mW to begin with.

A stack of junctions with a desired long-junction shape can be fabricated easily on the surface of a Bi-2212 or Tl-2223 single crystal by micropatterning a mesa structure and ion-beam dry etching as shown in Fig. 2(a). Since IJJs are stacked compactly, however, the motion of vortices in the mesa is strongly coupled to that of the basal stack situated underneath the mesa. That severely distorts the vortex motion in the mesa itself and impedes the ideal excitation of plasma oscillation. Thus, in order to remove the basal stack, we employ the so-called double-

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14. ABSTRACT
The contractor shall investigate THz-range active devices fabricated out of stacked intrinsic Josephson junctions on Bi-2212 or Tl-2223 single crystal by micropatterning a mesa structure and ion-beam dry etching.

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side-cleaving technique, which allows selecting a desired size (lateral size as well as the number of junctions) of stacked IJJs and patterning on both sides of the structure. The fabrication processes involving the double-side-cleaving is the most difficult part of the whole device preparation procedure.

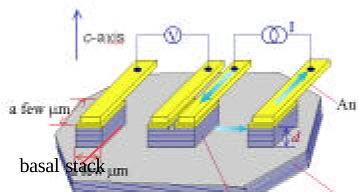

Fig. 2(a). A mesa of Bi-2212

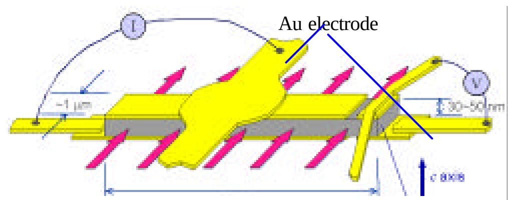

Fig. 2(b). A stack of Bi-2212 prepared by the double-side-cleaving technique.

To excite a coherent plasma oscillation it is utterly imp ortant to find a suitable tunneling-current bias condition. The plasma oscillation in stacked IJJs has distinct modes, whose number corresponds to the number of IJJs in the stack. Plasma modes are revealed in the current-voltage characteristics of a stack as multiple sub-branches. The rectangular vortex lattice corresponds to the mode with the fastest plasma propagation in IJJs. Thus, the proper bias condition can be obtained by fixing a stack to the branch corresponding to the fastest plasma-propagation mode of accurately measured multiple-sub-branch current-voltage characteristics.

A technical obstacle in realizing the THz radiation device is to convert the plasma oscillation inside a single crystal stack to the electromagnetic radiation in the free space at the stack boundary. Since the dielectric constant of the wave-propagating insulating layers is higher than 10, in comparison to about 1 of the free space, large impedance mismatch is bound to take place at the stack boundary. Thus, a sophisticated impedance matching scheme should be devised to allow the radiation to the free space. In this study, coupling with impedance-matching antennas will be employed to overcome the obstacle.

2) Research Accomplishments:

- Quantitative Identification of the Josephson-vortex-flow Submodes in $Bi_2Sr_2CaCu_2O_{8+x}$ Intrinsic Josephson Junctions [M.-H. Bae and H.-J. Lee, Physica C **426-431**, 61 (2005)]

Stacked intrinsic Josephson junctions form in highly anisotropic high-T_c superconductors such as $Bi_2Sr_2CaCu_2O_{8+x}$. Josephson vortex dynamics in such systems attracts much research interests, both academic and application points of view. In a dense Josephson-vortex state (in the range of 4-5 T external magnetic field applied in parallel with the junction planes) of $Bi_2Sr_2CaCu_2O_{8+x}$ stacked intrinsic Josephson junctions vortex-flow motion is in resonance with the collective plasma oscillation modes. With increasing magnetic fields beyond ~2 T hysteretic quasiparticle branches keep shrinking, while the collective Jospehson vortex-flow branches start appearing and become clearer. The Josephson vortex flow branches split into multiple sub-branches corresponding to the number of coupled junctions in the stack. The low-bias characteristics of the Josephson vortex-flow sub-branches fit well to the inductive-capacitive hybrid coupling model. The best-fit value of the capacitive coupling constant is 0.45, which is in the reasonable range of theoretical expectation. This study indicates that incorporation of the interlayer capacitive coupling with the inductive coupling is required to properly describe the Josephson-vortex-flow characteristics in serially stacked and multiply coupled Josephson junctions.

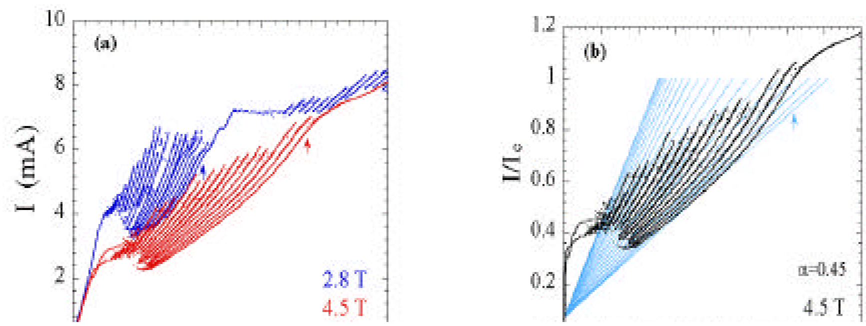

Fig. 2. (a) The current-voltage characteristics (IVC) for 2.8 T and 4.5 T. (b) The IVC for 4.5 T, where the current axis is normalized by the critical current for 4.5 T. The contact resistance was subtracted numerically. The straight lines are the best fit to the inductive-capacitive hybrid coupling model.

- Heating-excluded Tunneling Measurements on Stacks of $Bi_2Sr_2CaCu_2O_{8+x}$ Intrinsic Junctions [M.-H. Bae, J.-H. Choi, and H.-J. Lee, Applied Physics Letters **86**, 232502 (2005)]

In highly anisotropic layered cuprates such as $Bi_2Sr_2CaCu_2O_{8+x}$ tunneling measurements on a stack of intrinsic junctions (IJs) in a high-bias range are often susceptible to self-heating. In this study we monitored the temperature variation of a stack (``sample stack'') of IJs by measuring the resistance change of a nearby stack of IJs, which was strongly thermal-coupled to the sample stack (refer to the lower inset of Fig. 4). We then adopted a proportional-integral-derivative scheme incorporated with a substrate-holder heater to compensate the temperature variation. This in-situ temperature monitoring and controlling technique allows one to get rid of spurious tunneling effects arising from the self-heating. This technique is essential to obtain heating-effect-excluded true tunneling vortex flow characteristics.

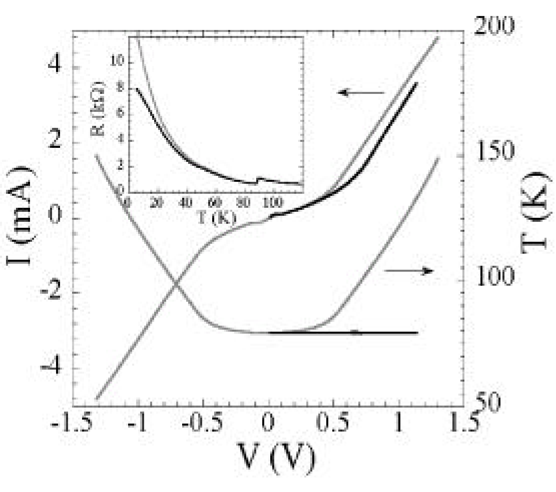

Fig. 3. I-V characteristics and temperatures of the sample stack as a function of the bias voltage without (gray curves) and with (black curves; only the positive-bias data were taken) the PID temperature control scheme. Inset: The R vs T curves of the sample stack near zero bias without (gray curve) and with (black curve) the bias current of 0.28 mA in the thermometer stack.

Observation of the Electromagnetic Wave Radiation from Intrinsic Josephson Junctions

[M.-H. Bae and H.-J. Lee, submitted to Physical Review B]

The existence of the collective transverse plasma modes excited by the motion of the Josephson vortex lattice in stacked intrinsic Josephson junctions (IJJs) of $Bi_2Sr_2CaCu_2O_{8+x}$ are confirmed, for the first time, by observing the magnetic-field dependence of multiple subbranches in the Josephson-vortex-flow current-voltage characteristics. The symptom of the microwave emission from the resonance between the Josephson vortex lattice and the collective transverse plasma modes, detected using another stack of IJJs placed in proximity to the oscillator stack (refer to the lower inset of Fig. 4), also provides additional confirmation of the existence of the collective transverse plasma modes and a possibility of developing THz-range Josephson vortex-flow local oscillators.

The magnetic-field dependence of multiple branches observed in the Josephson vortex-flow region of the tunneling I-V characteristics in stacked IJJs represents the structural transition of the Josephson vortex lattice along *c* axis. The microwave radiation from the resonant branches, as manifested by the changing of I-V curves in the detector stack, provides a possibility of utilizing the Josephson vortex dynamics in IJJs to develop the Josephson vortex-flow oscillator. The observation of the Shapiro steps in the detector stack would be the most convincing evidence of the microwave generation from the oscillator stack. But, the observation of the Shapiro steps requires stronger radiation power with improved matching between the oscillator stack and the external circuitry including the transmission line and the detector stack. Thus, devising the optimal impedance matching scheme is the most important step to be taken before the Josephson vortex-flow oscillator technique is put into practical applications. Impedance matching using antennas or dielectric wave guides can be considered.

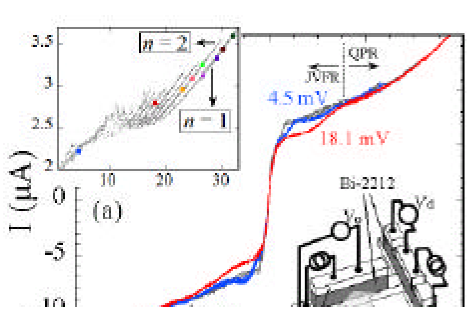

Fig. 4. The response of the detector stack, showing the modification of the vortex-flow branches due to irradiation of the THz-range microwaves from the oscillator stack. Upper inset: vortex-flow-branches of the oscillator stack with the bias points denoted by dots. Lower inset: sample configuration showing the oscillator stack (the left stack) and the detector stack (the right stack).

3) Relevance to current Air Force research or research interests:

There are growing application needs for THz radiation in fields such as multi-channel short-range communications, satellite remote sensing, radar modeling, chemical content analysis, non-destructive quality control of plastic parts and semiconductor chips, quantum-bit control, radio spectroscopy of heavy molecules, etc. The military application needs in diverse fields are also expected to grow rapidly in the near future.

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